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WIMP Mass Determination with Neutrino Telescopes

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Abstract

Weakly-interacting massive particles (WIMPs) annihilating in the center of the Sun or the Earth may give rise to energetic neutrinos which might be discovered by astronomical neutrino detectors. The angular distribution of the neutrino-induced muons is considered in detail via Monte Carlo simulations. It is shown that large underground Čerenkov neutrino telescopes might be able to extract the WIMP mass from the width of the muon angular distribution.

1 Introduction

Weakly-interacting massive particles (WIMPs) with masses in the GeV–TeV range are among the leading non-baryonic candidates for the dark matter in our galactic halo. One of the most promising methods for the discovery of WIMPs in the halo is via observation of energetic neutrinos from annihilation of WIMPs in the Sun [1] and/or the Earth [2]. Through elastic scattering with the atomic nuclei in the Sun or the Earth, a WIMP from the halo can lose enough energy to remain gravitationally trapped [3]. Trapped WIMPs sink to the core of the Sun or the Earth where they annihilate into ordinary particles: leptons, quarks, gluons and – depending on the masses – Higgs and gauge bosons. Because of absorption in the solar or terrestrial medium, only neutrinos are capable of escaping to the surface. Most WIMP candidates – among them the supersymmetric candidate, the neutralino – do not annihilate into neutrinos directly [4]. Nevertheless energetic neutrinos are eventually produced via hadronization and/or decay of the annihilation products. These energetic neutrinos may be discovered by astronomical neutrino detectors.

Trapped WIMPs are (to a good approximation) in thermal equilibrium with the core of the Sun and/or the Earth. The radial extension of the WIMP annihilation region is a function of the WIMP mass [5, 6], heavier WIMPs lying deeper in the core. This led Gould [7] to suggest that the WIMP mass might be inferred from the angular size of the annihilation region.

In this letter, we consider Čerenkov neutrino telescopes. They consist of large underground arrays of photo-multipliers to detect the Čerenkov light emitted by muons generated in charged-current interactions of neutrinos with the medium surrounding the detector. Underground Čerenkov detectors, originally built

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to search for proton decay, have already started to explore (and constrain) WIMP dark matter candidates [8].

Here we want to study if Čerenkov neutrino telescopes currently planned or under construction [9] might realistically expect to be able to extract the WIMP mass from the muon angular distribution (once measured). We include the uncertainties in the determination of the neutrino direction due to the neutrino-muon scattering angle in charged-current interactions, to multiple Coulomb scattering of the muon on its way to the detector and to an intrinsic angular resolution in the determination of the direction of the muon track.

2 Annihilation channels and muon fluxes

WIMPs trapped in the core of the Sun and/or Earth can annihilate to a fermion-antifermion pair, to gauge bosons, Higgs bosons and gluons ($\chi\chi \rightarrow \ell^+\ell^-, q\bar{q}, gg, q\bar{q}g, W^+W^-, Z^0Z^0, Z^0H^0, W^\pm H^\mp, H^0H^0$). These annihilation products will hadronize and/or decay, eventually producing high energy muon neutrinos.

Edsjö [10] reconsidered the whole chain of processes from the annihilation products in the core of the Sun or the Earth to detectable muons at the surface of the Earth. He performed a full Monte Carlo simulation of the hadronization and decay of the annihilation products using JETSET 7.3 [11], of the neutrino interactions on their way out of the Sun and of the charged-current neutrino interactions near the detector using PYTHIA 5.6 [11], and finally of the multiple Coulomb scattering of the muon on its way to the detector using distributions from Ref. [12].

With respect to previous calculations [13, 14], the Edsjö Monte Carlo treatment of the neutrino propagation through the Sun bypasses simplifying assumptions previously made, namely neutral currents are no more assumed to be much weaker than charged currents and energy loss is no more considered continuous. In the new treatment, the neutrino energy spectrum at the surface of the Sun is obtained as follows. The thickness of the Sun and the neutrino mean free path determine the probability of neutrino-nucleus interactions. Each interaction is randomly chosen to be a charged-current interaction, in which case the neutrino is considered absorbed, or a neutral-current interaction, in which case the neutrino is degraded in energy according to distributions in PYTHIA 5.6. The procedure is continued until the neutrino has reached the surface of the Sun. The resulting neutrino spectrum differs significantly from previous calculations only in the high energy tail. But from this high energy tail comes the most important contribution to the muon flux in Čerenkov neutrino detectors.³ Hence at a WIMP mass of 1500 GeV (50 GeV) Edsjö finds a muon flux 20% (5%) higher than that obtained by Ritz and Seckel [13].

For more details on Edsjö results, we refer the reader to Ref. [10]. In the following, we rely on his results obtained by simulating 10^5 WIMP annihilation events per annihilation channel and WIMP mass.

3 Annihilation profiles

The annihilation region in the Sun can be regarded as point-like, its angular size being $\lesssim 0.005^\circ$ for the WIMP masses we are interested in, $m \gtrsim 10$ GeV. For the Earth, on the contrary, the angular extension of the annihilation region is non-negligible and decreases as one over the square root of the WIMP mass [5]. In fact, the annihilation rate per unit volume at a distance r from the center of the Earth is proportional to the square of the WIMP number density $n(r)$. The latter may be written as

$$n(r) = n(0)e^{-r^2/2r_\chi^2}, \quad (1)$$

with

$$r_\chi = \left[\frac{3kT}{4\pi G\rho m} \right]^{1/2} \simeq \frac{0.56R_\oplus}{\sqrt{m/\text{GeV}}}. \quad (2)$$

Here we have taken the radius of the Earth $R_\oplus \simeq 6400$ km, the central Earth temperature $T \simeq 6000$ K and the central Earth density $\rho \simeq 13$ g cm⁻³. For the WIMP masses we are interested in, it is a very good approximation to consider a constant Earth density in the region where WIMPs are concentrated.

³We remind that this is so because the muon flux is the product of the neutrino flux by the charged-current cross section and the muon range, and both of these are proportional to the neutrino energy.

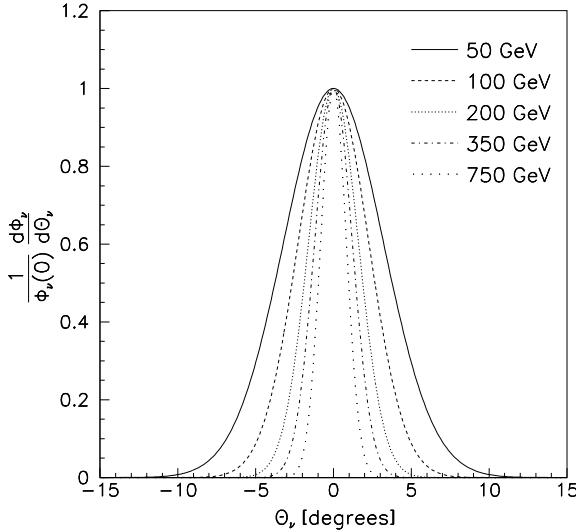


Figure 1: *Projected angular distributions of WIMP-generated neutrinos from the Earth for WIMP masses of (solid line) 50 GeV, (dashed line) 100 GeV, (dotted line) 200 GeV, (dash-dotted line) 350 GeV and (wide dotted line) 750 GeV. The analogous distributions from the Sun are simply a narrow peak at $\theta_\nu = 0$.*

For an observer close to the surface of the Earth the angular distribution of the neutrinos generated in WIMP annihilations results

$$\frac{d\Phi_\nu}{d\varphi_\nu d\cos\theta_\nu} \propto e^{-a^2 \sin^2 \theta_\nu} \text{erf}(a \cos \theta_\nu) \quad (3)$$

where θ_ν is the angle between the neutrino direction and the center of the Earth, φ_ν is the associated azimuthal angle, $a = R_\oplus/r_\chi$ and erf is the error function.

This expression simplifies in our case, $m \gtrsim 10$ GeV, for which θ_ν is typically smaller than 15° . In this case the θ_ν -distribution is simply approximated as a gaussian in the transverse plane, the plane orthogonal to the directions of either the Sun or the Earth centers,

$$\frac{d\Phi_\nu}{d\theta_x d\theta_y} \propto e^{-a^2(\theta_x^2 + \theta_y^2)}, \quad (4)$$

where θ_x and θ_y have obvious meaning.

To reduce the fluctuations due to limited statistics it is more convenient to consider the projected distribution in θ_x . From Eq. (4) we find that the projected distribution can be considered gaussian,

$$\frac{d\Phi_\nu}{d\theta_x} \simeq \Phi_\nu(0) e^{-a^2 \theta_x^2}, \quad (5)$$

with root mean square value

$$\theta_\nu^{rms} \simeq \frac{1}{\sqrt{2}} \frac{r_\chi}{R_\oplus} \text{rad} \simeq \frac{23^\circ}{\sqrt{m/\text{GeV}}} \quad (m \gtrsim 10 \text{ GeV}). \quad (6)$$

Projected angular distributions of the neutrino flux from the Earth are shown in Fig. 1 for WIMP masses between 50 and 750 GeV. The distribution width decreases for increasing WIMP masses. Note that these distributions are independent of the neutrino energy spectrum and of the specific annihilation channel. The analogous distributions for the Sun are simply narrow peaks at $\theta_\nu = 0$.

4 Muon angular distributions

In Čerenkov neutrino telescopes it is not possible to measure the angular distribution of the neutrinos directly since it is the muon produced in charged-current interactions that can be detected. The direction

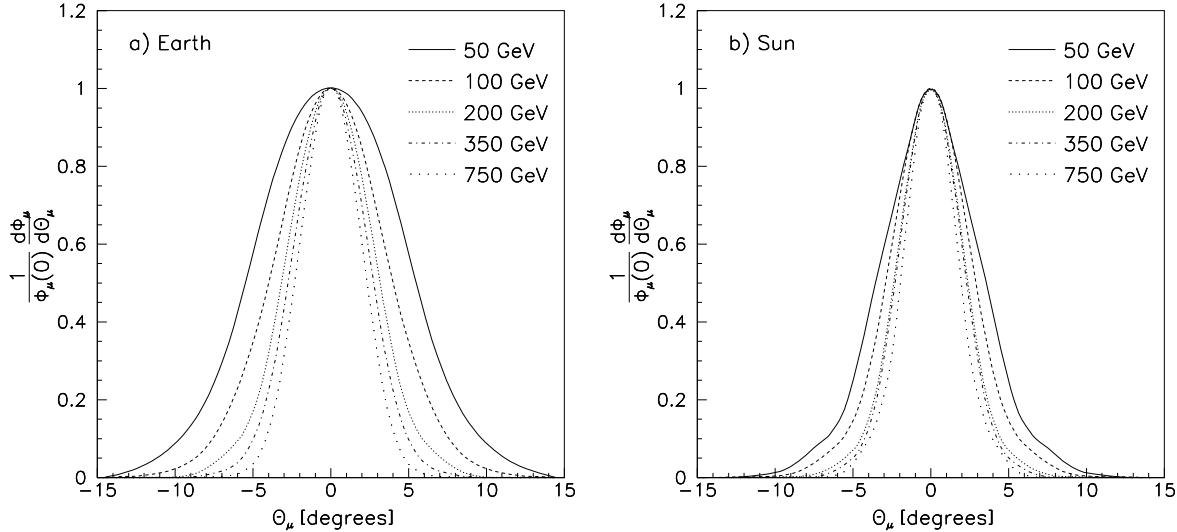


Figure 2: *Projected angular distributions of neutrino-induced muons from WIMP annihilations in (a) the Earth and (b) the Sun for WIMP masses of (solid line) 50 GeV, (dashed line) 100 GeV, (dotted line) 200 GeV, (dash-dotted line) 350 GeV and (wide dotted line) 750 GeV. The distributions are shown for hard channels (W^+W^- for 100–750 GeV and $\tau^+\tau^-$ for 50 GeV), with a detector muon threshold $E_\mu^{th} = 10$ GeV and a detector angular resolution $\theta_{det} = 1.4^\circ$.*

of the neutrino is somewhat lost because of two effects: (1) the muon produced in a charged-current interaction exits at an angle θ_{CC} with respect to the incoming neutrino and (2) the same muon undergoes multiple Coulomb scattering on its way to the detector, changing direction by an angle θ_{Coul} . Both angles are approximately gaussian in the transverse plane (at least in the central region, for θ_{CC} has non-gaussian tails) with root mean square values

$$\theta_{CC}^{rms} \simeq \frac{19^\circ}{\sqrt{E_\nu/\text{GeV}}} \quad (E_\mu > 10 \text{ GeV}) \quad (7)$$

and

$$\theta_{Coul}^{rms} \simeq \frac{3.1^\circ}{\sqrt{E_\mu/\text{GeV}}}, \quad (8)$$

where the first relation is obtained by simulations with PYTHIA 5.6 and the second relation is from Ref. [12]. Notice that both angles get smaller with increasing neutrino (and muon) energy.

There is an additional uncertainty coming from the reconstruction of the muon track. Each neutrino telescope has an intrinsic angular resolution in determining the direction of the muon. We assume that the error in its determination is normally distributed with root mean square value θ_{det} , typically of the order of 1° .

In Fig. 2 we plot the muon angular distributions for hard channels in the Earth and in the Sun, obtained from the full Eds   simulations in [10]. These distributions are representative of any hard neutrino spectrum. For a neutrino spectrum to be hard it is not necessary that it is dominated by a hard channel, like W^+W^- , Z^0Z^0 and $\tau^+\tau^-$. Because of the previously-mentioned importance of the high energy tails, it suffices that the branching ratio into hard channels is greater than $\sim 10\%$. Softer neutrino spectra, *e.g.* those from the $b\bar{b}$ and H^0H^0 channels, give rise to wider angular distributions. This is due to the energy dependence of θ_{CC}^{rms} and θ_{Coul}^{rms} . Note the difference between the neutrino (Fig. 1) and muon (Fig. 2) angular distributions: charged-current interactions and multiple Coulomb scattering make the width dependence on WIMP mass stronger.

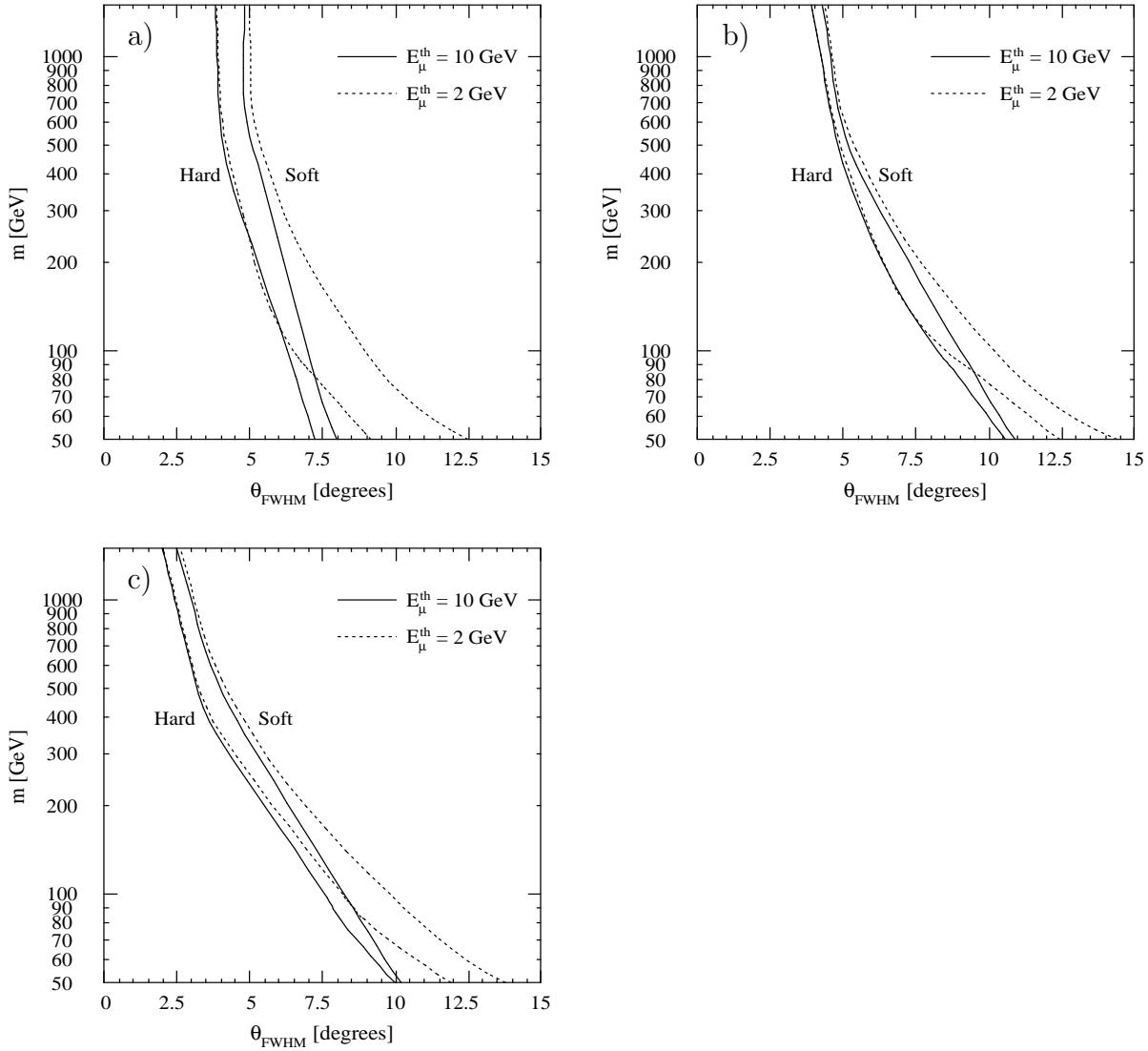


Figure 3: WIMP mass m versus full width half maximum θ_{FWHM} of the neutrino-induced muon distribution for soft ($b\bar{b}$) and hard (W^+W^- and $\tau^+\tau^-$) channels. The solid lines correspond to $E_\mu^{th} = 10$ GeV and the dashed lines to $E_\mu^{th} = 2$ GeV. a) For Sun-bound WIMPs with a detector angular resolution of $\theta_{det} = 1.4^\circ$. b) For Earth-bound WIMPs with a detector angular resolution of $\theta_{det} = 1.4^\circ$. c) For Earth-bound WIMPs with a perfect angular resolution.

5 WIMP mass determination

Information on the WIMP mass might be extracted from the width of the distribution in the transverse plane. With limited statistics it might be convenient to project this two-dimensional distribution onto the θ_x axis. As a measure of the width we choose the full width half maximum θ_{FWHM} of the projected distribution. The FWHM is not sensitive to the non-gaussian tails of the distribution, which reflect the non-gaussian tails in θ_{CC} . Moreover, as long as the detector resolution θ_{det} is small with respect to θ_{FWHM} , it should be relatively easy to extract the FWHM even in the presence of a background (muons and neutrino-induced muons from cosmic ray interactions in the atmosphere).

In Figs. 3a-c we show the dependence of the WIMP mass on the full width half maximum for some representative cases. We present the soft $b\bar{b}$ -channel and the hard W^+W^- - and $\tau^+\tau^-$ -channels for the

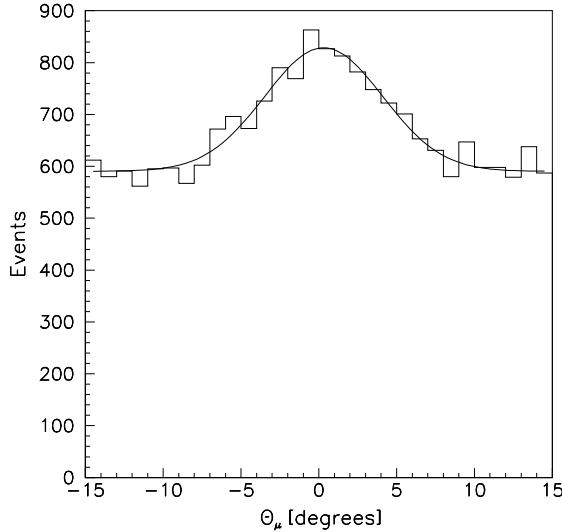


Figure 4: An example of mass determination from a projected muon angular distribution. The simulated histogram includes the expected background in one year of exposure with a 1 km^2 detector and a typical signal from annihilation of 100 GeV WIMPs in the Earth. The solid line is a fit of a gaussian plus a constant.

Earth and the Sun for two different muon energy thresholds, $E_\mu^{th} = 2 \text{ GeV}$ and $E_\mu^{th} = 10 \text{ GeV}$. Figs. 3a and 3b include a detector angular resolution $\theta_{det} = 1.4^\circ$. For the sake of comparison, Fig. 3c shows the ideal case of a perfect angular resolution. We have checked that all distributions are indeed well approximated by gaussians in the central regions.

We see that the detector angular resolution is the limiting factor for the mass determination of heavy WIMPs ($m \gtrsim 400 \text{ GeV}$). For lighter WIMPs, it seems promising to infer their mass from the Earth muon distributions. We remind that this is also the mass range in which the signal from the Earth is expected to be significant [6]. The WIMP mass could also be extracted from the Sun muon distributions provided the detector muon energy threshold is low. In fact, the width of the angular distribution for the Sun is dominated by charged-current scattering, which acts as a mass spectrometer in diffusing neutrinos according to their energies and so according to the WIMP mass.

From Figs. 3a, 3b and analogous ones, approximate relations between the error on the WIMP mass and the error in θ_{FWHM} may be obtained. For example, for $E_\mu^{th} = 10 \text{ GeV}$, $\theta_{det} = 1.4^\circ$ and $m \lesssim 300 \text{ GeV}$, we read from Fig. 3b

$$\Delta \log m \simeq 0.15 + 0.15 \Delta \theta_{FWHM} \quad (9)$$

with $\Delta \theta_{FWHM}$ in degrees. The first term represents our ignorance on the actual annihilation channel and the second term comes from the slope of the $m - \theta_{FWHM}$ curve. For $\Delta \theta_{FWHM} \sim 1^\circ$, relation (9) gives an uncertainty on the WIMP mass of roughly a factor of 2.0.

We present now an example of mass determination for Earth-bound WIMPs. We consider one year of exposure of a 1 km^2 detector with a muon energy threshold of 10 GeV. The atmospheric background in the direction of the center of the Earth is expected to be 20 muons per square degree [15]. We choose a WIMP mass of 100 GeV and generate a signal of 2000 muons, a reasonable number for supersymmetric models with neutralinos of this mass. In this way we obtain a simulated muon angular distribution in a $15^\circ \times 15^\circ$ region centered towards the center of the Earth. We then analyze these simulated data. We project the muon distribution onto the θ_x axis and obtain the histogram shown in Fig. 4. By fitting a gaussian plus a constant to this histogram we obtain a full width half maximum $\theta_{FWHM} = 8.9^\circ \pm 0.7^\circ$. From Fig. 3b we then read the WIMP mass range corresponding to the fitted FWHM range, $m = 90^{+50}_{-25} \text{ GeV}$. We are satisfied that the mass range obtained contains the original WIMP mass. The uncertainty is approximately a factor of 1.5, in agreement with the approximate relation Eq. (9). One might worry about the size of the uncertainty, but we believe that even a rough determination of the WIMP mass would be of enormous importance. We are exploring ways to reduce this uncertainty.

In favorable cases, many muon neutrinos might be detected from both the Earth and the Sun. Having both angular distributions, the angular smearing due to charged-current interactions and multiple Coulomb scattering would be directly represented by the Sun muon distribution (recall that the annihilation region in the Sun can be considered pointlike). This distribution might then be subtracted from the Earth muon distribution, leaving the neutrino angular distribution from the Earth. From it the WIMP mass could be obtained in a direct way via Eq. (3). Notice that for heavy WIMPs ($m \gtrsim 100$ GeV) one should correct for absorption of neutrinos on their way out of the Sun, *e.g.* by specifying the shape of the neutrino energy spectrum.

6 Conclusions

WIMPs annihilating in the center of the Sun or the Earth may give rise to a neutrino-induced muon flux in astronomical neutrino detectors. The width of the muon angular distribution carries information on the WIMP mass, because the size of the annihilation region, the charged-current neutrino-nucleon scattering and the multiple Coulomb scattering of the muons all depend on the WIMP mass. Detailed Monte Carlo simulations have been used to obtain the muon angular distribution for WIMP annihilations in the Earth and in the Sun. It has been shown that the WIMP mass can be inferred, for WIMPs lighter than ~ 400 GeV, from the Earth distribution and, provided the muon energy threshold is low ($\lesssim 5$ GeV), also from the Sun distribution. This seems therefore a promising method of determining the WIMP mass and we look forward for the detection of a WIMP signal in neutrino telescopes.

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